Dynamically balanced first wall for the LiWall tokamak-reactor

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Abstract

The shape of the dynamically balanced first wall has been calculated. The wall structure includes: a) $\simeq$1 cm thick intense plasma facing lithium streams driven by magnetic propulsion, b)$\simeq$ 1 mm thick patchy separation guide wall, c) Be wire ropes balancing the structure (total maximum thickness of the set $\simeq$1 cm), d) $\simeq$1 mm patchy second separation layer, and e) $\simeq$ 10-15 cm thick Zinkle-Nelson FLiBe blanket. While the existing design approaches to the reactor essentially mimic the large plasma experiments and fail to satisfy all basic requirements of the reactor physics and cost, the presented first wall structure is the first conceptual design which is consistent with the high neutron flux, efficient power extraction as well as with high performance plasma regimes.

Supporting material for the talk can be found on the web-page http://w3.pppl.gov/~zakharov

OUTLINE

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2. New plasma physics regime and the LiWalls concept.
3. Yacht-sail approach for the first wall.
4. Force balance and the shape of the first wall.
5. Summary.

1 Basics of the tokamak power reactors design

In designing the power reactor there is a very little room for maneuver.

The most important characteristics, such as

- plasma regime, i.e. β, τ_E,
- size and range of the total power,
- low recycling plasma edge regime and power extraction scheme from the plasma,

are predetermines by the very basic level of tokamak reactor physics.

In addition, basic requirements for the neutron zone predetermine

- a FLiBe based power extraction scheme from the blanket

with minimal use of high-Z materials.

Ignition criterion is a fusion specific requirement for the reactor operation

$$n \cdot T \cdot \tau_E > 5 \cdot 10^{21} \quad \left[\frac{1}{\mathrm{m}^3} \cdot \mathrm{keV} \cdot \mathrm{sec}\right]. \tag{1.1}$$

Substitution

$$n \cdot T = B^2 \cdot \beta \cdot 1.25 \cdot 10^{21} \tag{1.2}$$

converts it into a suitable form

$$\boxed{B^2 \cdot \beta \cdot \tau_E > 4 \quad \left[\mathrm{T}^2 \cdot \mathrm{sec}\right]}$$

for the reactor design analysis.

Power of fusion reactor:

$$P_{tot}\ [\text{GW}] = 5P_\alpha = \frac{5E_{plasma}}{\tau_E}\ \left[\frac{\text{GJ}}{\text{sec}}\right], \qquad (1.3)$$

$$E_{plasma}\ [\text{GJ}] = \frac{3}{2}p_{thermal}V \simeq= \frac{3}{2}\beta B^2 V\ \left[\text{T}^2\cdot 10^3\text{m}^3\right].$$

Combining with

$$\beta B^2 \tau_E = 4, \qquad (1.4)$$

the power is simply

$$P_{tot}\ [\text{GW}] = 5\cdot\frac{3}{2}\cdot\beta\cdot\frac{B^2}{2\mu_0}\cdot\frac{V}{\tau_E}\ \left[\frac{T^2\cdot 10^3\text{m}^3}{\text{sec}}\right] \qquad (1.5)$$

or

$$\boxed{P_{tot} = 3\frac{\beta B^2 V}{\tau_E} = 12\frac{V}{\tau_E^2} = 0.75\beta^2 B^4 V}$$

Two simple but fundamental formulas

$$\boxed{P_{tot}\,[\mathrm{GW}] = 12\frac{V}{\tau_E^2}\left[\frac{10^3\mathrm{m}^3}{\mathrm{sec}^2}\right],} \qquad \boxed{\beta B^2\tau_E = 4\ \left[\mathrm{T}^2\cdot\mathrm{sec}\right]}$$

and the \$-value of electricity produced

$$\begin{aligned} S &\simeq (?)\frac{P_{tot}}{4}\cdot(30\ \text{years})\cdot 365\cdot 24\cdot(0.04\,\$/kWh)\cdot 10^6 \\ &= 10.5\frac{P_{tot}}{4}\,\$\ \cdot 10^9, \end{aligned} \tag{1.6}$$

determine the strategy of the power reactor.

ITER based approach with $\tau_E = 3.7$ sec and $\beta = 0.025$ is inconsistent with it.

Low plasma β is a key unresolved problem of magnetic fusion

In order to fit the cost requirements for the reactor with $P_{tot} \simeq 4-5$ GW

- The plasma volume should be cut by a factor of 2-3 with respect to ITER
- The energy confinement time should be about $1-1.5$ sec.
- β should be enhanced to the level of 15 %.

At the same design, on the ignition stage τ_E should be enhanced to the level of $4-5$ sec in order satisfy the heating power requirements

$$P_{ext} \simeq P_\alpha \simeq 1.2 \frac{V}{\tau^2_{E,4ignition}}. \tag{1.7}$$

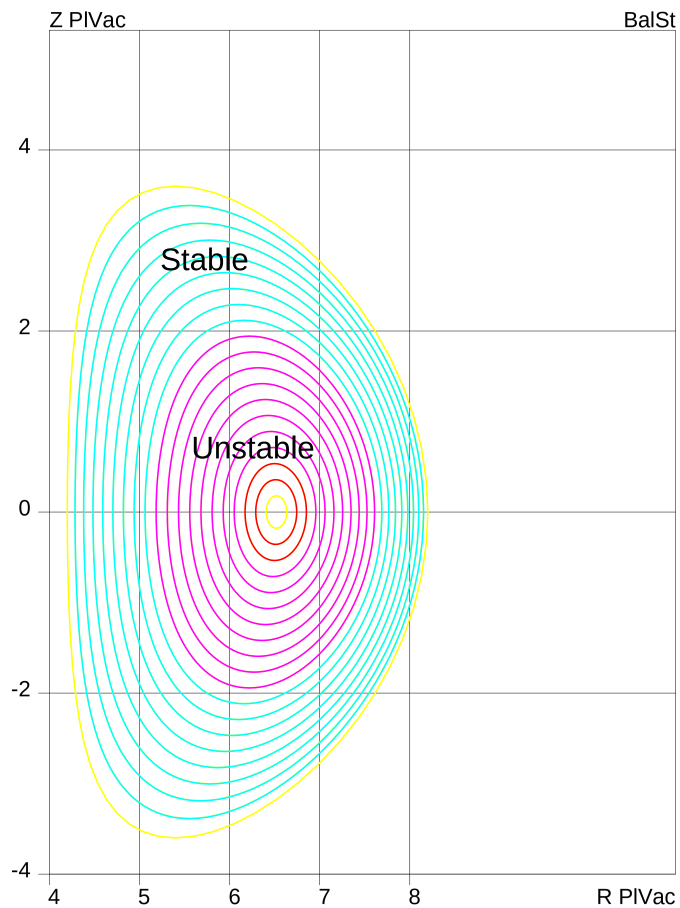
2 New plasma physics regime and the LiWalls concept

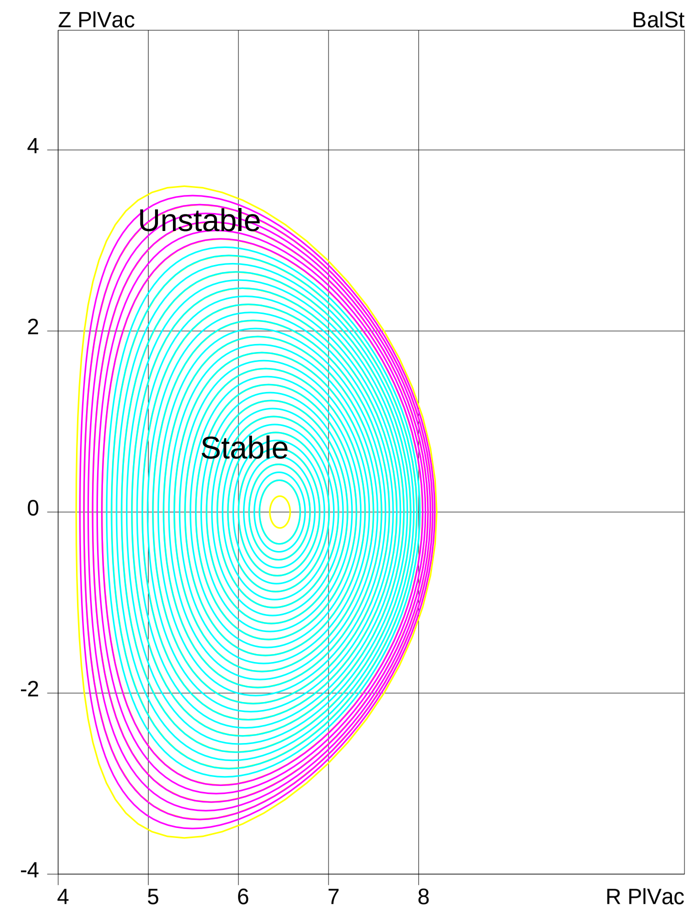
Without new plasma regime there in no hope for a fusion power reactor.

The logic of such a regime is:

1. The only way of enhancing β is to switch to a wall stabilized plasma.
2. This is still not sufficient (at least, for tokamaks). Troyon criterion still limits β at unacceptable low level.
3. The only way to bit it is to switch to the low recycling plasma regime with either
   (a) Lithium plasma facing renewable wall, or
   (b) pumping (rather that radiating) divertor (a la Mike Kotschenreuter)
4. Low recycling regime, which is sensitive to the boundary conditions, is the only regime with controllable τ_E, which, e.g., can be kept high at the ingnition phase, and reduced at during burning.

Even with wall stabilized plasma conventional profiles are limited in β

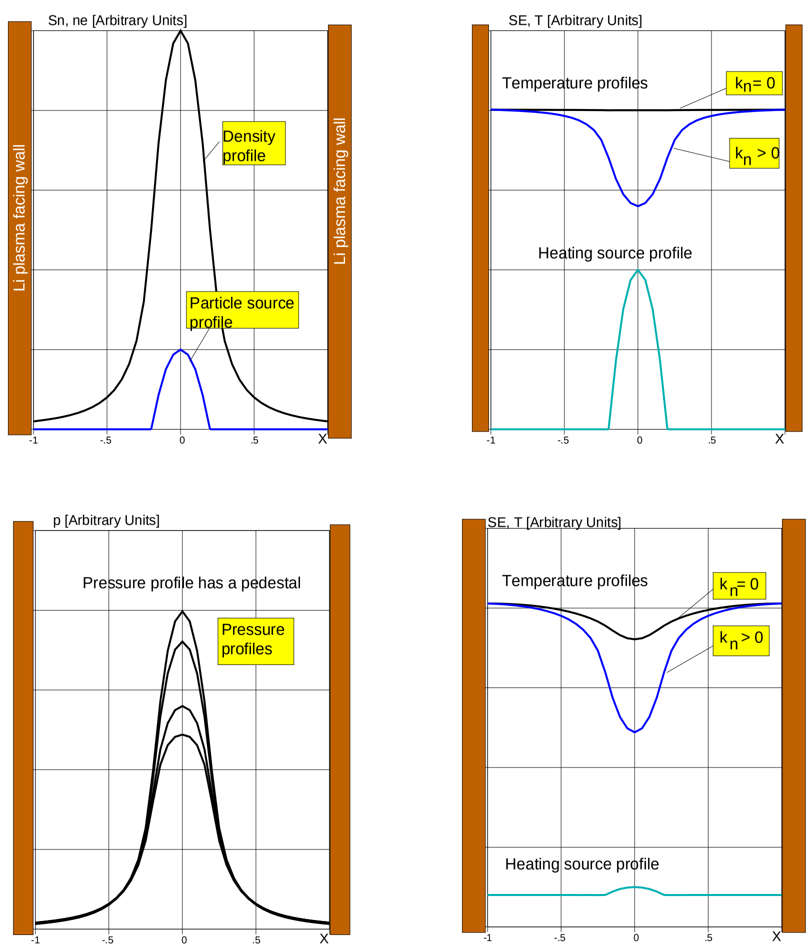




Unstable at $\beta = 4.5$ %
(Peaked pressure)

Unstable at $\beta = 5.0$ %
(Less peaked pressure)

In low recycling plasma is fueled by injection rather than through the boundary



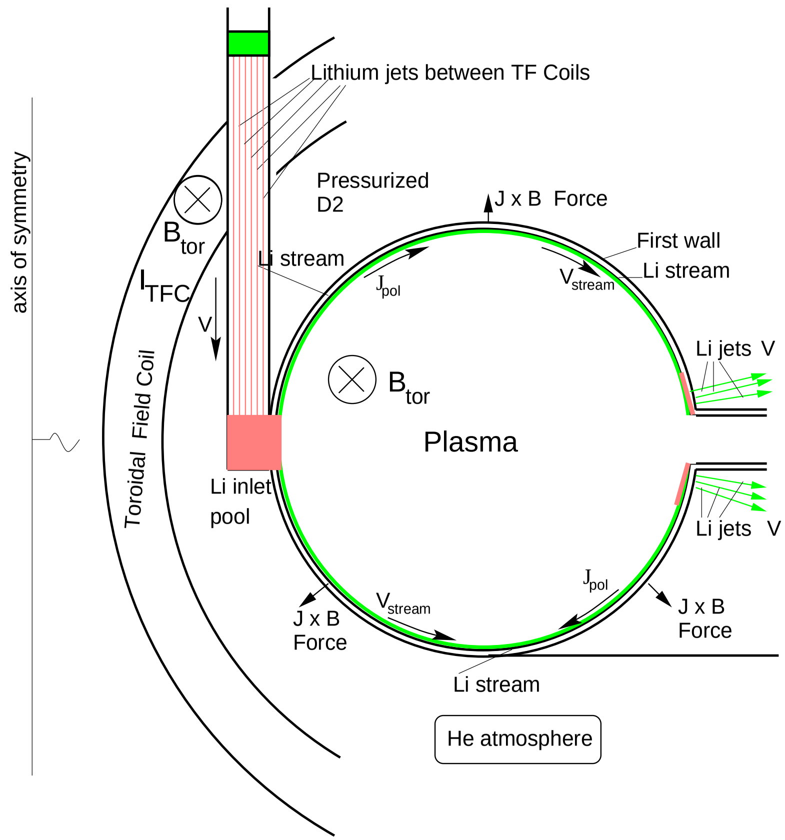
DENSITY profile (left) is predetermined by the core fueling.

TEMPERATURE profile (right) adjusts itself in order to ELIMINATE the thermo-conduction.

PRESSURE profile (left) has a jump at the plasma boundary.

TEMPERATURE profile (right) eliminates the thermo-conduction irrespective to the heat source profile.

Intense Li streams are the key element of the LiWalls concept



- Driving electro-magnetic pressure

  $$p_{j\times B}\big|_{outlet} > 1\ atm$$

  $$p_{j\times B}\big|_{inlet} - p_{j\times B}\big|_{outlet} \simeq 1.5 - 3\ [atm$$

- Flow parameters

  $$V \simeq 20\ m/sec, \quad h \simeq 0.01\ m$$

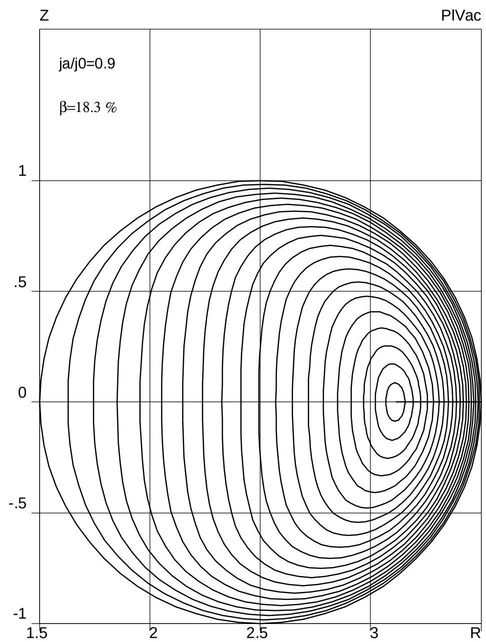
- Magnetic Reynolds numbers

  $$\Re_1 \equiv \mu_0\sigma h V \simeq 0.8, \quad \Re_2 \simeq 0.0015$$

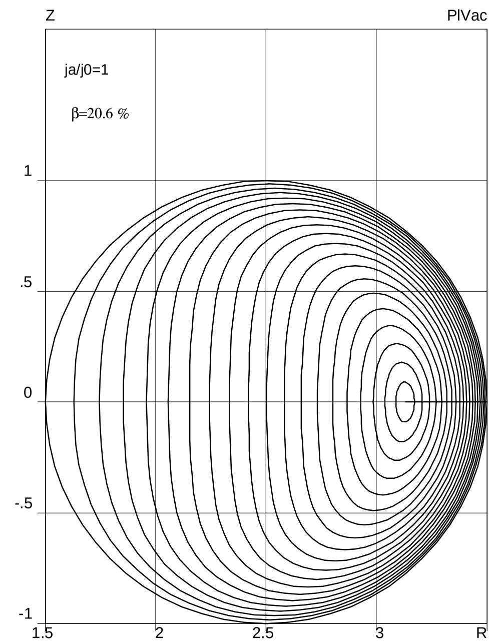
- Stream are robustly stable due to centrifugal force

  $$\rho\frac{\langle V^2\rangle}{2} > \frac{a}{2R} p_{wall} n_r$$

LiWalls open the high β path to reactor



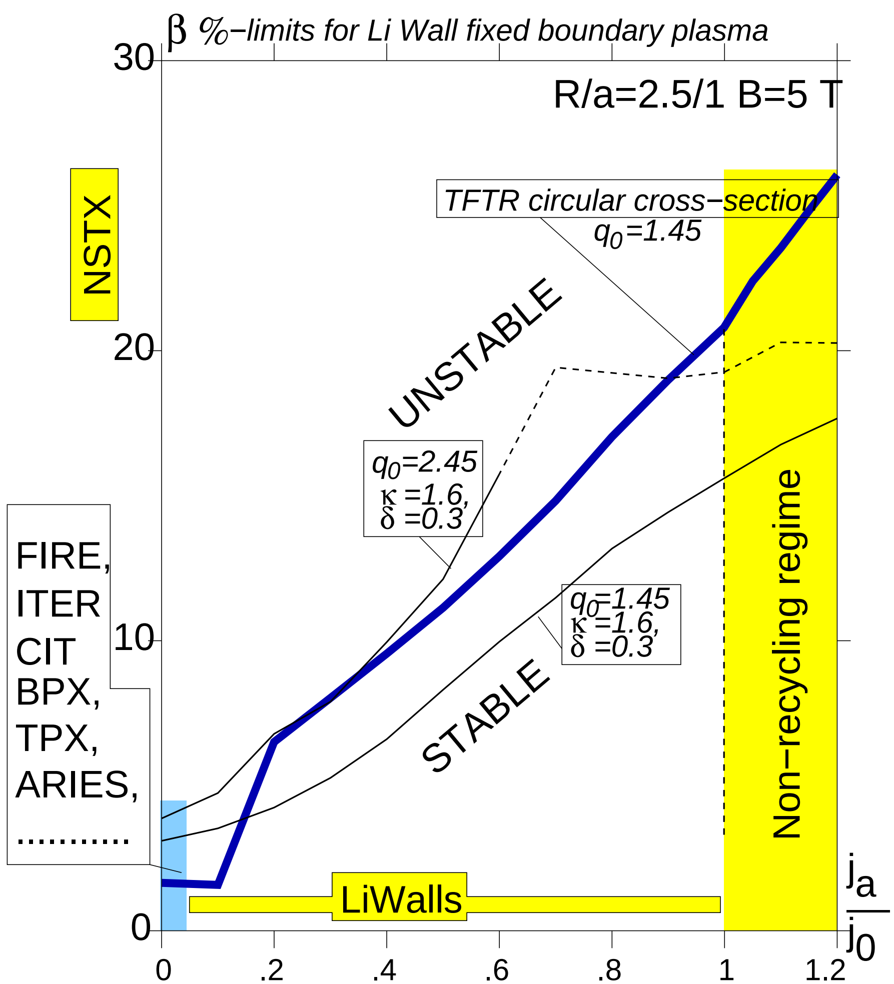
$\beta = 18\%$



$\beta = 21\%$

LiWalls high-β configurations relevant
to the non-recycling regime

LiWalls lead to the core second stability regime



- no sawtooth oscillations;
- no Troyon limit;
- the second stability core;

β - limits for the second stability regime

- fixed boundary plasma
- n=1,2,3 + ballooning modes (DCON,PEST-2,BALLON,ESC)
- current density with an edge pedestal

$$\mathbf{j}_{\|} = j_a + (j_0 - j_a)\left(1 - \frac{r^2}{a^2}\right)$$

LiWalls have extraordinary power extraction capabilities

With the flight time $t_{flight} \simeq 0.25$ sec

$$\boxed{q_{wall} \simeq 3.5 \text{ MW/m}^2, \quad (+14 \text{ MW/m}^2 \text{ in neutrons}), \quad \Delta T < 200^o,}$$

even with no vortices in the streams.

E.g., for a middle size tokamak-reactor

$$\boxed{R = 6\, m, \quad a = 1.6\, m, \quad P_{wall} = 4\pi^2 R a q_{wall} \simeq 1.3\, GW,}$$
$$\boxed{P_{tot} = 6.5\, GW}$$

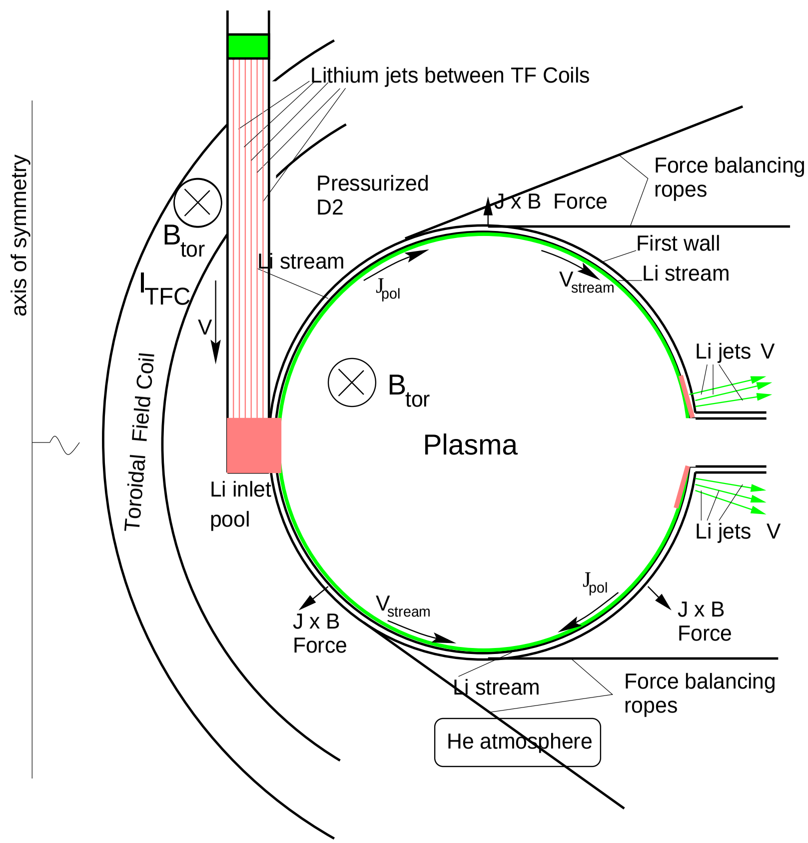
3 Yacht-sail approach for the first wall

The “first wall” (first 10-15 cm) is the most challenging element of the fusion reactor

- surface absorption of 1/5 of the fusion power flux
- absorbing most of remaining 4/5 of the fusion power
- conversion of the neutron power into the high-temperature coolant
- trithium breeding
- withstanding deterioration of mechanical properties
- withstanding possible abnormal thermal or electromagnetic plasma events
- be consistent with low activation

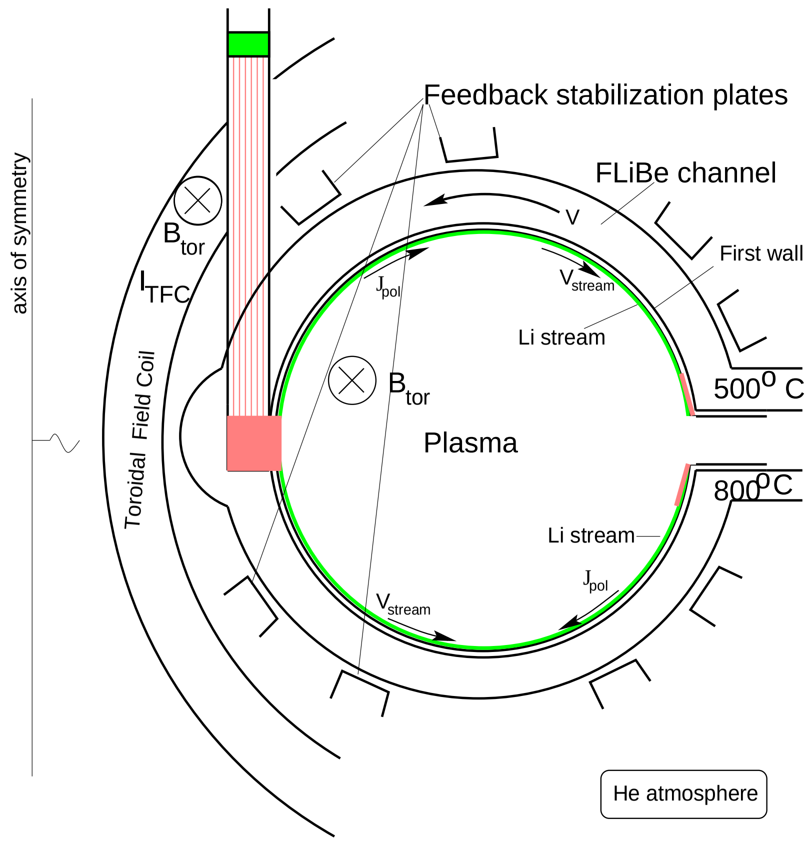
Intense Li Streams affect the very fundamentals of reactor desing.

Electrodynamic pressure creates a stable situation for the first wall.



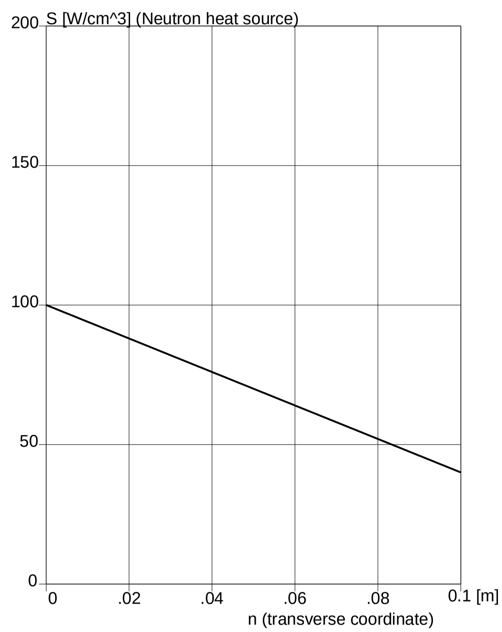
- Guide wall works against expansion $\Longrightarrow$
- Guide wall can be made as a thin shell (like a car tire).
- Inner surface is sealed by the lithium streams (insensitive to cracks) $\Longrightarrow$
- Vacuum barrier can be moved to the plasma boundary (giving access to the neutron zone).

The first wall in LiWall concept consists of

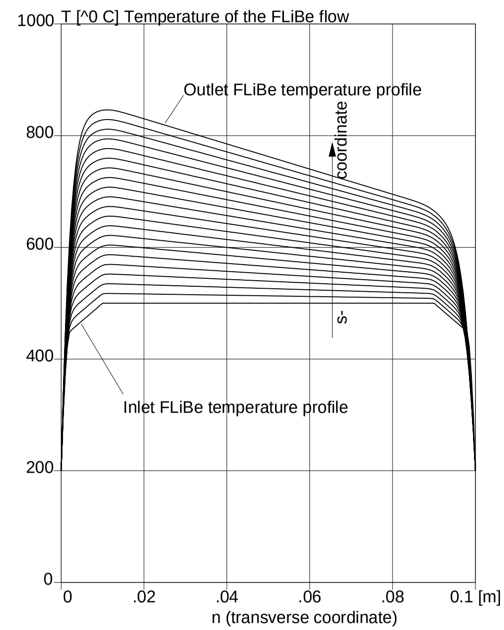


- Guide wall for intense Li streams (mm's in thickness)
- Force balancing Be wire ropes (about 1 cm total thickness)
- Zinkle-Nelson high-temperature FLiBe blanket (about 15 cm in thickness)

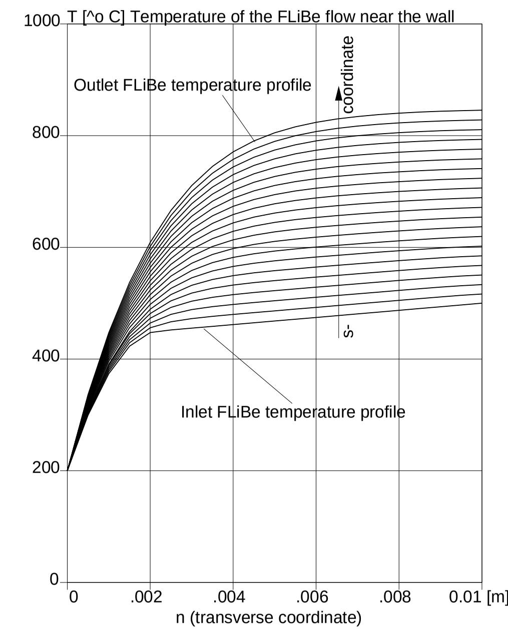
Active cooling of the guide wall makes FLiBe consistent with the reactor



n-heat source profile



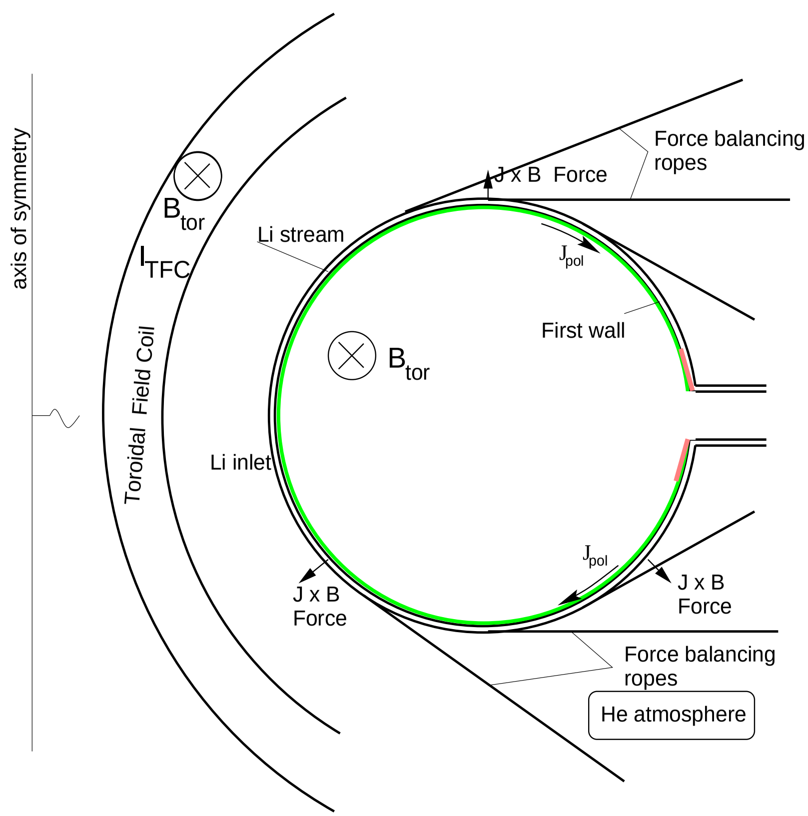
T accross the channel



T near wall

Even with $T \simeq 800^o\ C$ at outlet, the FLiBe channel has very small heat losses 4-5 %.

Yacht-sail is a new approach to mechanics and neutronics of the FW



- Guide wall serves only as a separator (made, e.g., from patches of wire fabrics).
- Be ropes are the only approach for the high neutron flux. Can be replaced on fly.
- Be ropes are consistent with trithium breeding.
- Wire ropes + FLiBe blanket is the best approach for the plasma control.
- Activation is minimal in the neutron zone.
- Deformations of the wall can be corrected on the fly.

LiWalls create the stationary boundary conditions for the plasma

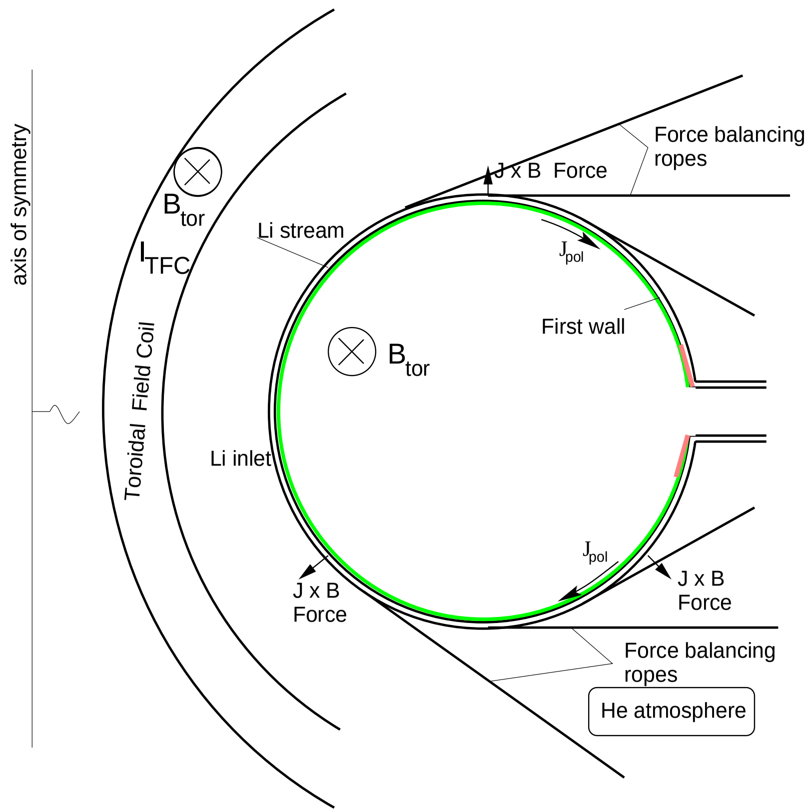
At the same time its first wall is insensitive to thermal deformations.

Thus,

LiWalls eliminate the necessity in the stationary regime of tokamaks.

4 Force balance and the shape of the first wall

Wire ropes can control the shape of a patchy guide wall

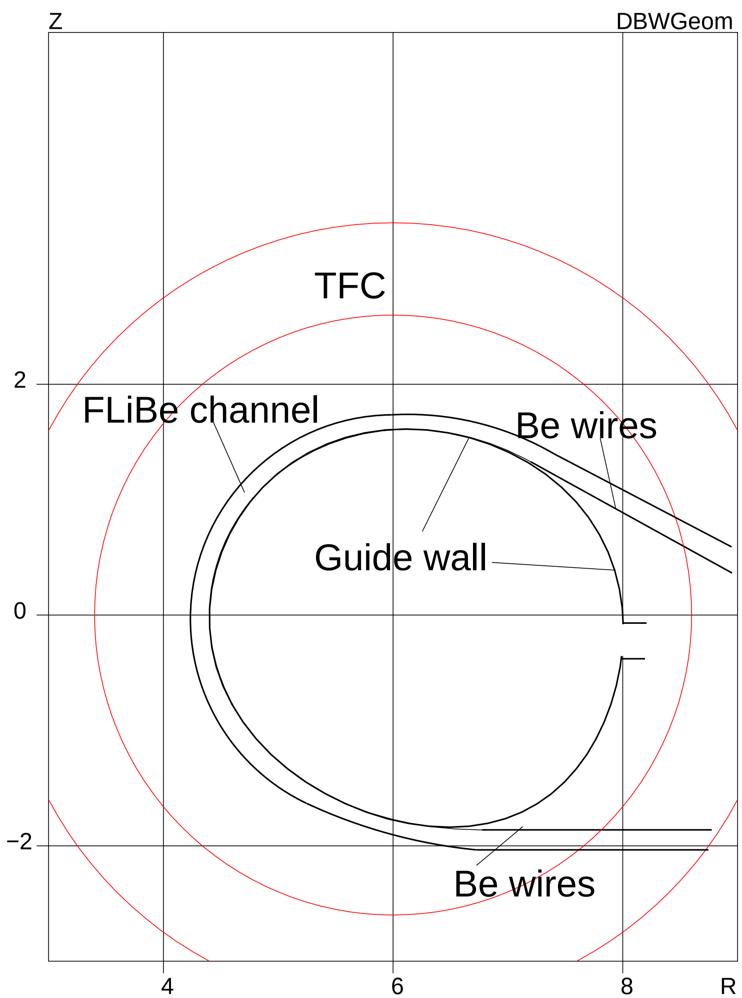


- Radial component of the electromagnetic force can be balanced if

$$\left(p_{\mathrm{j}\times\mathrm{B},outlet}\frac{r^2_{outlet}}{r^2} - p_{atm}\right)\frac{r}{r_{inlet}} = Td,$$

where T is the tension of ropes, $d(r)$ is the total height as a function of a touch point r.

Topology of Be wires can be made consistent with the presence of the FLiBe blanket



Equation for poloidal guide wall curvature

$$\boxed{\frac{dT}{\rho} = p_{IxB} - p_{ext} - g\rho_{FLiBe}(z - z_0)}$$

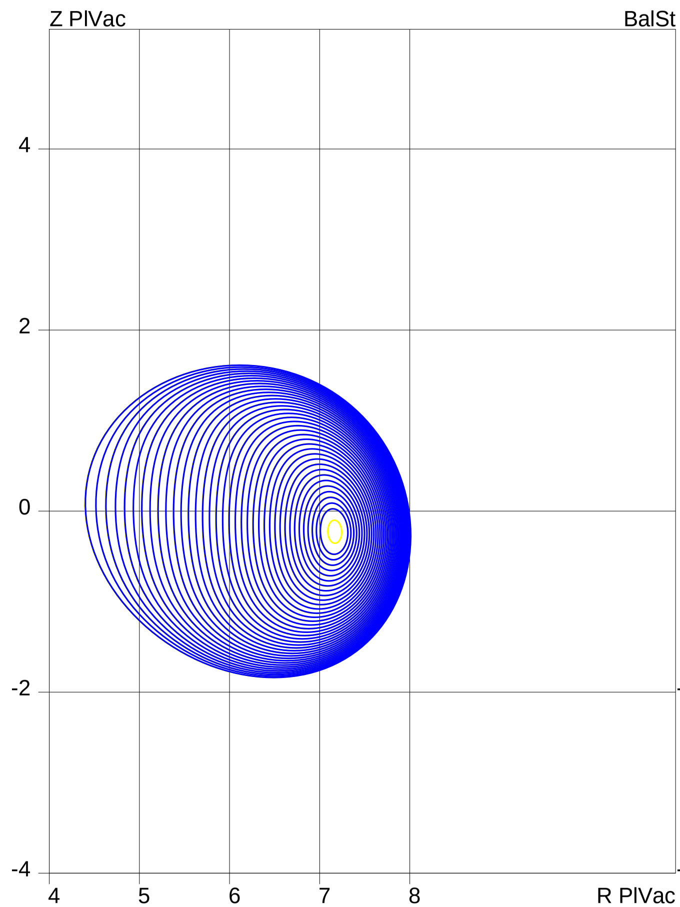
Radial force on both lines of wires

$$F = 1.5 \text{ [MN/m]}$$

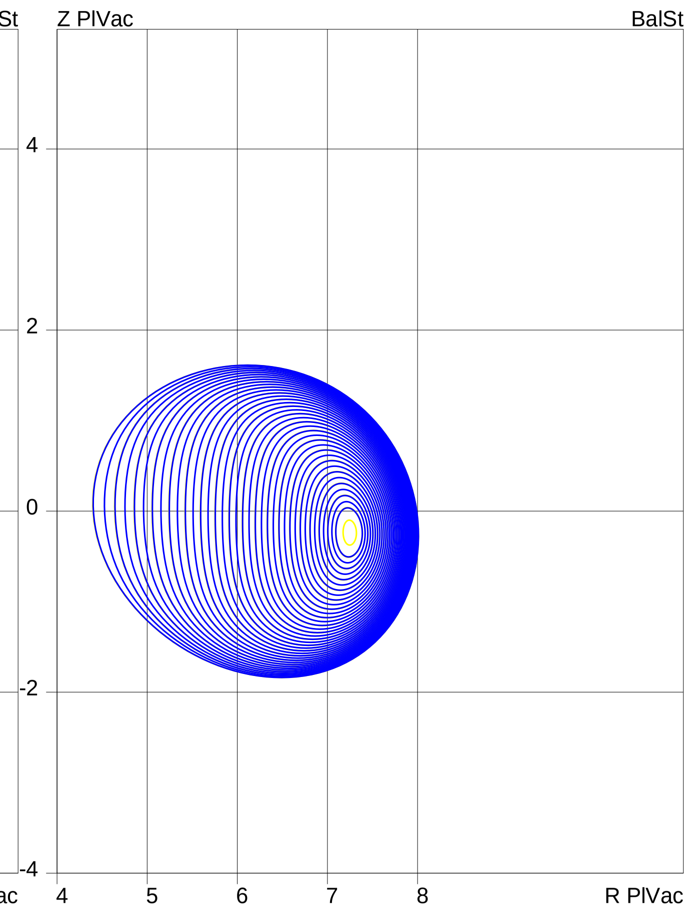
Tension in wires

$$d \cdot T = 0.75 \text{ [MPa} \cdot \text{m]}$$

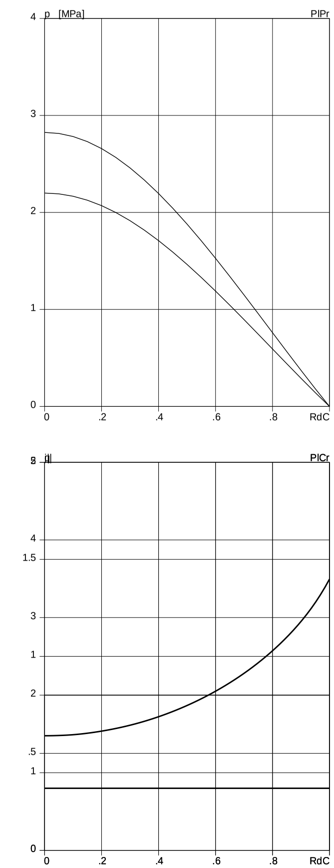
LiWall plasma shape remains consistent with high β



Stable $\beta = 10.1$ %



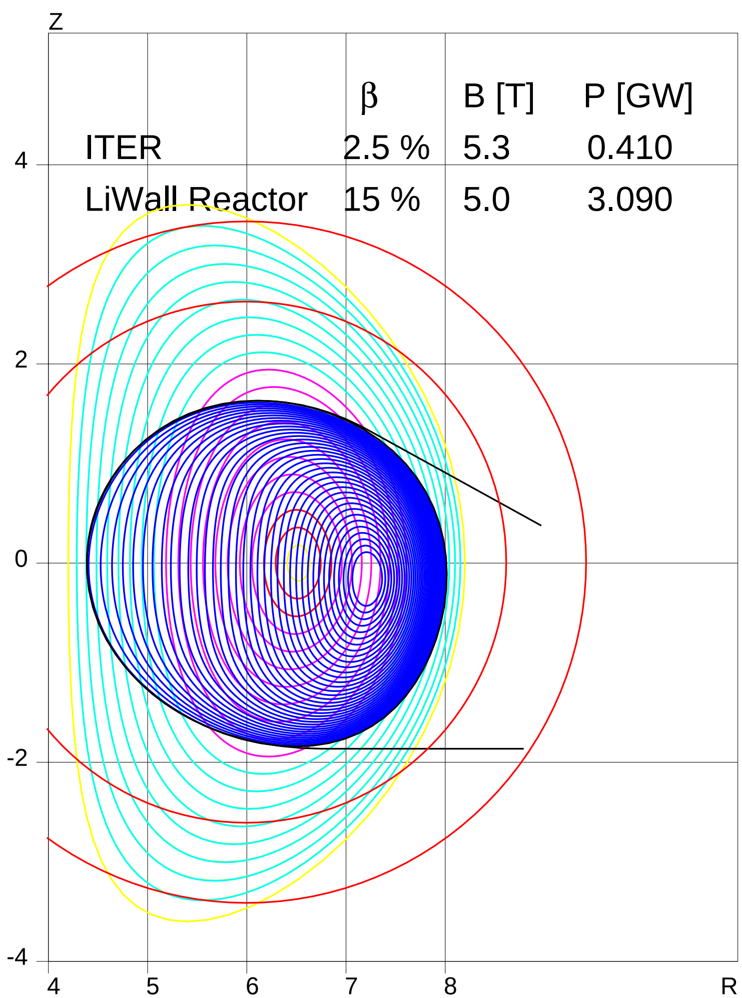
Stable $\beta = 14.3$ %



$p, q, j_{\|}$ profiles

5 Summary

LiWalls suggests new approaches to fundamentals of power reactors



Conceptual consistency with the reactor physics

Objectives	ITER path	LiWall	Mike K.
High beta	-	+	+
Low recycl.	-	+	+
τ_E contr.	-	+	+
Pl Pwr Extr.	- -	+-	+
n-Pwr Extr	-	+	+
FLiBe Bl.	-	+	+
Low Activ	-	+	-+
Mechanics	-	+	-+
Cost	-	+	-+

Mimicking the plasma physics experiments does not work for the power reactor. New ways are required.